LIGHTNING WARNING SYSTEMS

FOR

EXPLOSIVE OPERATIONS/FACILITIES

by

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ABSTRACT

This report presents a review of lightning warning techniques with emphasis on explosive facilities and operations. An explanation of how each technique is used to detect the presence of conditions that can lead to these discharges, with the advantages and limitations of these techniques is given. In addition, an attempt is made to show how the lightning detection hardware can be incorporated into a facility's Hazardous Weather Plan.

I. INTRODUCTION

Lightning can pose a severe safety hazard during explosive manufacturing and handling operations due to very strong electric and magnetic fields that are produced. Each of the services of the Department of Defense recognize this threat and require that explosive operations be curtailed at the approach of a thunderstorm. However, little guidance is given to the responsible party in determining when a thunderstorm is about to appear over his facility. In response to this problem, the Naval Sea Systems Command (NAVSEA 04H) has tasked the Naval Surface Weapons Center to investigate the current state-of-the-art in lightning detection technology and determine the effectiveness of each technique in applications involving explosive operations. This paper is a preliminary report of the information gained from the first phase of the program. It will review current lightning detection techniques available to explosive facilities and describe how each technique can be used to provide an advance warning of thunderstorm activity.

LIGHTNING DAMAGE MECHANISMS

The protection of a structure from the effects of lightning is based on statistical considerations of key lightning parameters. Even though facilities that house explosive materials are well protected, it is often not economically feasible to provide complete (100%) protection even to a "one-of-a-kind" facility. For this reason, it is essential to have an advance warning of lightning activity to terminate all explosive operations, or to evacuate all non-essential personnel from the area when termination of operations is not practical.

Lightning damage mechanisms are both mechanical and electrical in nature. The heat produced in the lightning channel by return stroke currents, which can reach 200 kA (200,000 amps), is adequate to burn holes in metal plates at the attachment point, fuze wires, burn through insulators such as glass, and cause explosions in masonry and trees due to the rapid expansion of trapped moisture. The 30,000 ^{o}K temperatures generated in the channel produces pressures of over 400 psi. The expansion of the channel produces a strong cylindrical shock wave whose pressure decreases with the square of the distance from the channel, until it becomes thunder. In addition, the return stroke currents produce mechanical forces which can crush metallic conduits, pull wires from walls, and arc through insulating materials. These mechanical effects are generally associated with a direct lightning strike and typically result in much physical damage at the point of attachment.

In contrast to the mechanical damage mechanisms, the electrical damage mechanisms can also be caused by distant lightning. Each lightning stroke produces an electromagnetic wave due to the rapidly changing return stroke current. This electromagnetic pulse induces currents in closed loops of wire and exposed conductors such as overhead power lines, telephone lines, instrumentation lines, and detonator leads. The resulting surges can cause severe damage due to arcing if not properly protected.

With the advent of plant modernization came the increased use of solid-state electronics in explosive operations. These electronic devices are much more susceptable to transient over-voltages and surges, requiring much less energy to cause catastrophic failure. The use of devices of this type in

manufacturing facilities where an immediate shutdown is not practical, requires that a programmed shutdown be inititated well before a thunderstorm reaches the facility. However, equally important are the economic considerations due to a shutdown when no lightning hazard exists.

The primary task of the Thunderstorm Hazards to Ordnance Research (THOR) program is to determine when explosive operations should be curtailed due to lightning hazards and define the warning levels adequate for each type of warning technique. This is a very complex problem and will take the reduction of years of lightning detection data from differing geographical locations.

WARNING REQUIREMENTS

The first step in selecting a warning device is to determine how much advance warning is required. As stated earlier, lightning can create a hazardous condition well before it reaches the location of the explosive operation. In addition, the spatial separation of successive strikes is about 3km (2mi.) with separations of up to 10km (6mi.) recorded.

The amount of warning time required from a lightning detection system will vary considerably from facility to facility. The following factors influence the amount of warning time necessary:

1. Type of operations being conducted and the sensitivity of the ordnance being handled in that configuration -

   For example, a missile in its "all-up" configuration with electrical out-of-line devices is much less sensitive than a detonator with its firing leads attached. In addition, the sensitivity of electronic control systems must also be considered in modern manufacturing plants where an immediate shutdown introduces an unacceptable hazard.

2. Length of time required to terminate operations -

   Explosive operations that require only minutes to terminate need less sophisticated warning systems than will a manufacturing plant that may require an extended period to complete a programmed shutdown.

3. Schedule criticality -

   Sites with little incidence of lightning activity can afford to be much more cautious in terminating operations than a site that will experience greater than 60 thunderstorm days per year. For operations whose scheduling is critical, the early warning of lightning activity is a critical problem.

4. Location of operations -

   The orographic effect due to the location of the facility is often critical in determining the type of storm warning necessary. Mountains and large bodies of water often provide some of the conditions necessary for the development of

thunderstorms. Facilities near orographic features such as these may find a larger number of storms building directly over their facility than would a plant in a flat, open area. Storms also tend to follow these features in terrain during their normal movement. In addition, the geology of the area can be important. Lightning has been observed striking in a valley just below cliffs that are composed of high resistivity earth.

5. Typical storm characteristics -

   An experienced observer at an ordnance facility can often forecast the onset of a thunderstorm because of the years of observation of the characteristics of these storms. Some of these characteristics are the type of storm normally experienced, typical direction of speed of storm movement, typical times of day of storm occurance, and normal ambient conditions leading to storm. The experienced observer can use the observed deviation in these characteristics to see how useful each can be when trying to decide whether to terminate operations or not.

The relative importance of each of these factors will vary with each individual operation. In addition, some operations may have some factor that influences the type of warning system necessary that is peculiar to that particular operation only. Therefore, before selecting a warning system each operation performed at the facility should be considered.

II. LIGHTNING WARNING TECHNIQUES

It is not yet possible to make accurate lightning forecasts for any given location, but it is possible to detect the occurance of distant lightning and detect the conditions that can lead to lightning, and thus a nearby discharge. Some detection techniques are still primarily research tools and are not yet advanced enough to be used reliably as a warning device. An example of these are the detection of the optical and audible spectrum of lightning. Research in these areas have not been directed toward lightning location except in crude form. For example, the difference in propagation time between the light and sound waves produced by lightning is used today at many facilities for locating the distance from a storm. AFR 127-100 states that a storm is "in the vicinity" when the difference in time between seeing the lightning flash and hearing the thunder (referred to as flash-to-bang time) is 15 seconds or less, which places the flash about 3 miles away. However, as reported earlier, the spatial difference in successive flashes can be as much as 6 miles. Moore, et. al. (1982), suggests that if the flash-to-bang technique is used for lightning location, at ordnance facilities, the storm should be considered in the vicinity when this time reaches 30 seconds or less.

The flash-to-bang technique has some serious limitations. Uman (1969) reports a case where thunder was not audible from a storm only 5 miles away. If the flash-to-bang technique is used, it is imperative that the responsible authority also know the speed of the movement of the storm at the time it approaches the vicinity of the facility. This speed can vary greatly from storm to storm, averaging 10 to 45 miles per hour, and even during the same storm. Although thunder can be heard from as much as 15 miles away, the operations carried out at ordnance testing facilities can mask this thunder until the storm is already "in the vicinity".

The flash-to-bang technique is prone to false alarms, also. Due to irregularities in the velocity and direction of storm movement, it is impossible to determine whether or not the storm will pass over the facility. This technique therefore is limited to applications at facilities which have few thunderstorm days per year and the scheduling of operations is not critical.

WEATHER FORECASTS

Local radio and television weather forecasts are generated with information from the National Weather Service, based on the statistical analysis of many meteorological inputs. These forecasts only predict the probability of a thunderstorm occuring during the day in the given forecast area. This does not mean that the storm will pass over the facility. This method is unreliable when used alone due to the expansiveness of the forecast area and the lack of a defined time when the storm will occur.

NATIONAL WEATHER SERVICE

In addition to the climatological data supplied by the weather service, weather radar is often used to determine the location of thunderstorm activity. Kasemir (1976) reported that it is probably the temperature rather than altitude that determines the onset of electricification. However, the higher the altitude a cloud reaches, the lower the temperature becomes.

CHARGE DISTRIBUTION OF TYPICAL CLOUD CELL

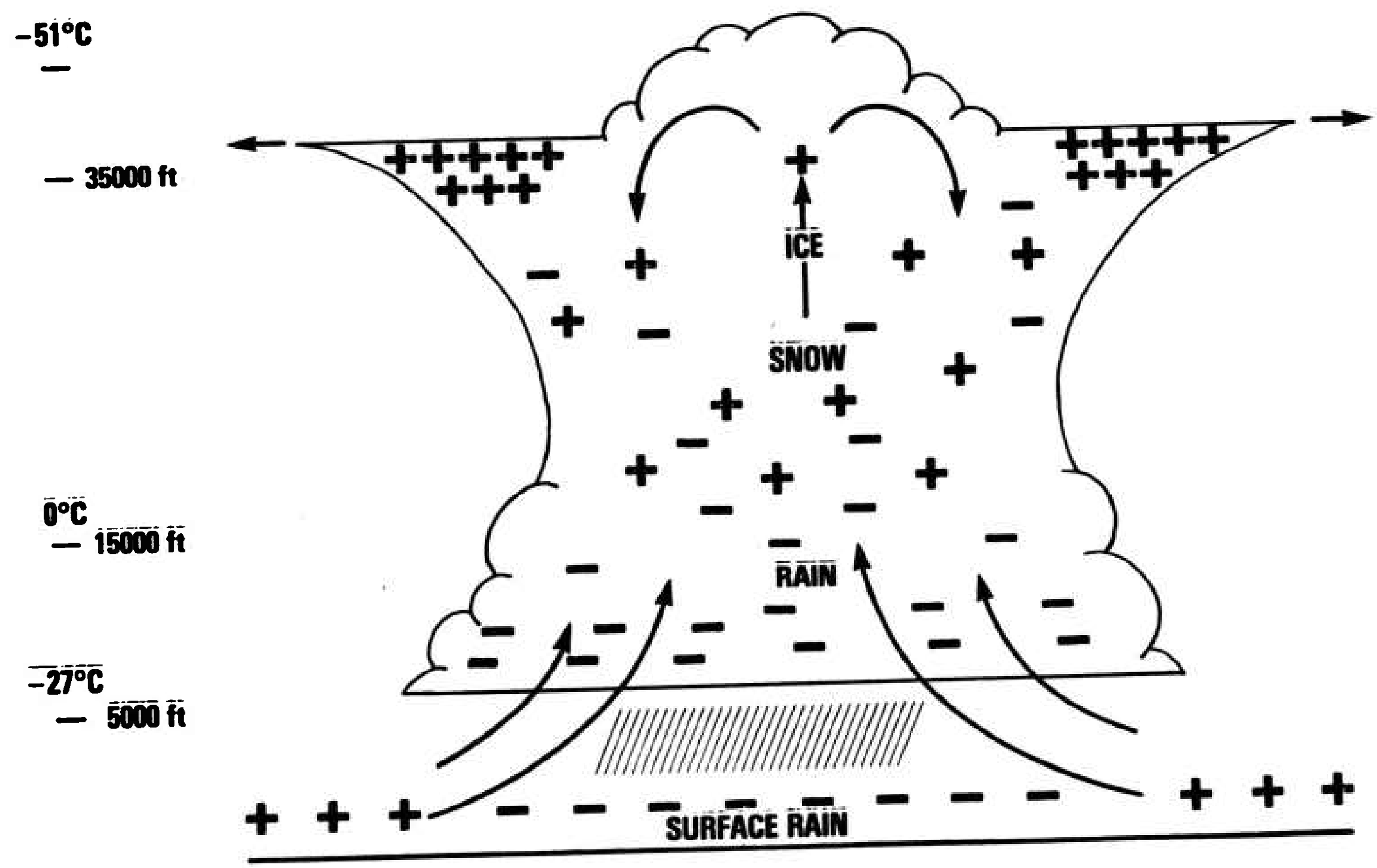

Figure 1

EXAMPLE OF RECORDING OF ΔE FIELD DETECTION INSTRUMENT

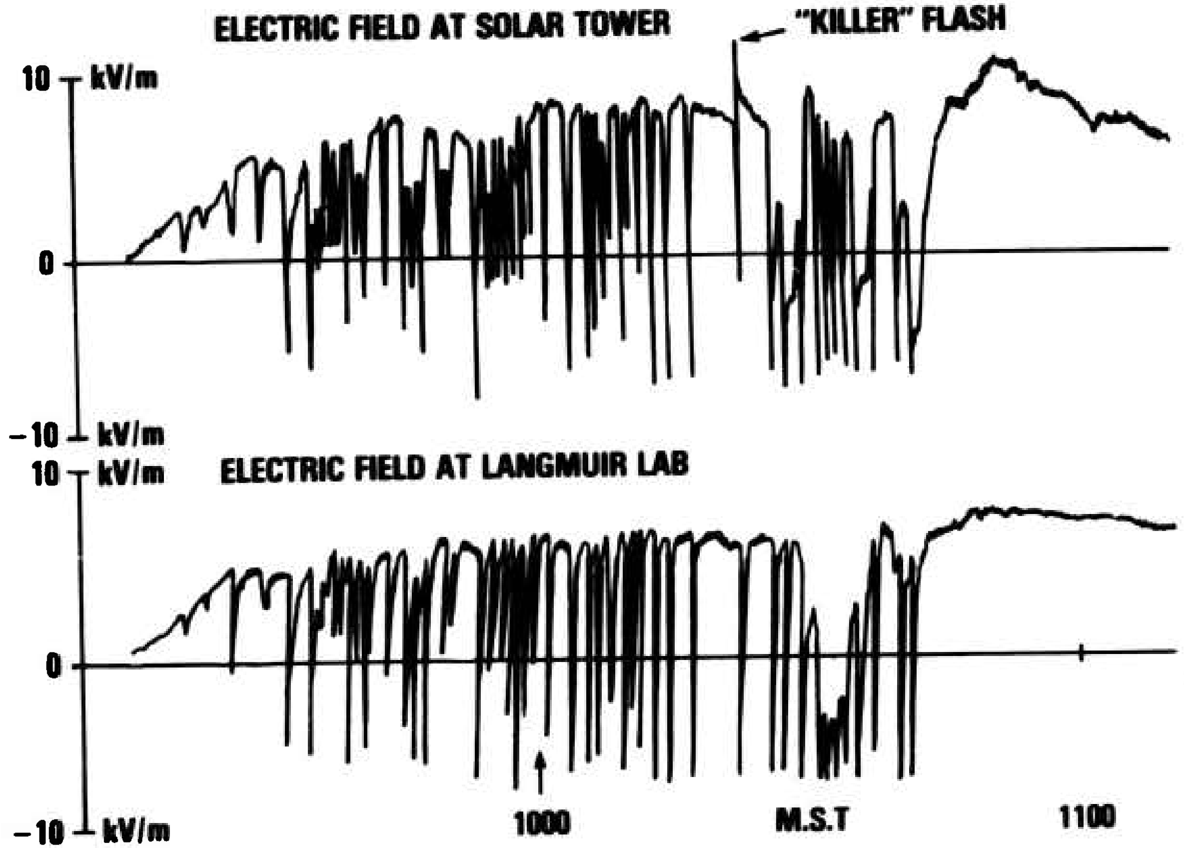

Figure 2 (courtesy of C. B. Moore
New Mexico Institute of Mining and Technology)

Cumulus clouds with tops below 16,000 feet do not contain electric fields adequate to generate cloud-to-ground lightning. When these cloud altitudes reach 25,000 feet or more, the fields in the cloud reach adequate levels to generate breakdown.

The National Weather Service radar displays can accurately identify the precipitation center of a cloud and determine from the density and altitude of the radar reflection whether this cloud is likely to contain lightning activity. However, Burger (1967) cites events showing that detonation of explosive devices can occur as much as 5 miles from the precipitation center of a storm. In addition, the radar data available is approximately 30 minutes old before it is released and the position of the storm could be as much as 15 to 20 miles off from the actual location by the time the information is used.

ELECTRIC FIELD MEASUREMENT

Under fair weather conditions, the electric field at the surface of the earth is generally +100 V/m. As a thunderstorm begins to build, the electric field gradient starts to increase. This change in the static electric field can be detected and then used to determine when local conditions are adequate for lightning to occur.

Changes in the static electric field can signal the approach of a storm. Figure (1) illustrates the charge distribution of a typical thunder cloud cell. As a charged cell approaches, the fair weather field becomes masked by the positive charge in the top of the cell, increasing the amplitude of the electric field gradient. As the cell gets closer, the negative charge at the base of the cell becomes more prominant and the electric field begins to change polarity. As the cell moves directly overhead, the electric field reaches its maximum negative value. Once the cell passes the measuring point the field again reverses polarity and finally relaxes to its fair-weather value.

FIELD MILL

The "field mill" is the most accurate and widely used device to measure the static atmospheric electric field. It measures the strength and polarity of the local electric field by having it alternately charge and discharge an electrode, which produces an alternating current whose amplitude is proportional to the magnitude of the external electric field. The information produced by the field mill is normally output on a strip-chart recorder to observe the onset of cloud electrification and track the passage of a storm.

In addition, the fast response time of the field mill allows it to detect the electric field changes produced by lightning. Figure (2) shows the output of a field mill for a storm recorded by C. B. Moore on 7 August 1979. The sharp discontinuities in the trace are due to lightning. The magnatude of the field change due to this lightning is somewhat proportional to the distance from the discharge. Most field mills marketed today use a combination of the static and dynamic electric field measurements to determine whether a lighting hazard exists.

The field mill can clearly indicate the presence of electrically disturbed weather patterns, but it has limitations. The device can only measure the atmospheric disturbances for the area immediately overhead, which can limit its warning time. In addition, it is easily influenced by the presence of space charge due to corona from nearby objects which can mask a much larger field strength aloft. To illustrate, Kasemir (1976) has detected lightning discharges when the surface field was only 600 V/m even though point discharge does not normally occur at field strengths below approximately 3000 V/m. Finally, the field mill is a sensitive research tool that is difficult to interpret when more than one storm cell is present, requires maintenance at periodic intervals, is sensitive to site location, and a go/no go criteria for alarm is difficult to establish. However, used in an array with the go/no go criteria specified in NAVSEA OP-5 (2000 V/m), the field mill can be a valuable tool for a safety director in evaluating the development of hazardous conditions due to lightning.

CORONA CURRENT

The corona current detector is the simplest measuring technique that can be used to determine the onset of a thunderstorm. As discussed earlier, strong electric fields are generated in thunderstorms, however, these fields are rarely observed to reach values over 15 kV/m over land surfaces. This phenomenon is due to corona discharges that occur at the tips of trees, bushes, towers, and other sharp objects attached to the earth. The space charge generated by the corona creates a screening layer that reduces the magnitude of the electric field at the ground. Although this space charge can limit the effectiveness of a field mill due to this screening, its generation can be used to detect potentially hazardous conditions.

A sharp point raised some height above a ground plane (earth) causes an enhancement of the atmospheric electric field around the point. This discharge process is initiated in a small volume of air close to the tip. As electrons are accelerated in the field, collisions with gas molecules ionize these gas molecules which release more electrons. This process, called electron avalanche, continues until a corona discharge is produced to decrease the concentration of the local electric field.

The value of the corona current produced by the point depends on the strength of the electric field, the presence of other points in the area, height of the point, curvature of the tip, and local wind speed. Therefore, for a given wind speed, the corona current is directly proportional to the electric field strength.

Although simple to build and instrument, the corona current detector has limitations. The wind speed is very important when determing warning levels of corona current. In addition, the system is not responsive to field strengths of less than approximately 1000 V/m, resulting in little advance warning.

RADIOACTIVE PROBE

Radioactive probes can also be used to measure the atmospheric electric field. These probes can be designed to measure either corona currents or voltage potentials; although all devices available commercially measure only

the voltage potentials. In either case, the radioactive material (polonium or tritium) is used as a source of ionization. Though their response time is slow, the probes are reliable and accurate.

In contrast to the corona current detector, the radioactive probe is less reliable in calm winds than in strong winds. In addition, the radioactive source must be changed about once a year to maintain adequate sensitivity.

SPHERICS

A sudden change in current flow will produce an electromagnetic wave that can be detected from a considerable distance. The waves produced by lightning currents are capable of propagating thousands of miles even though the strength of the signal decreases with distance. It is estimated that over the surface of the earth there are approximately 100 flashes every second. These waves are trapped by the earth's atmosphere and form a continuous background of crackling noise (static) on all but the highest frequency bands. These radiated waves, called atmospherics or spherics, can be detected and used to determine the actual location of the lightning discharge.

FLASH COUNTER

The flash counter is a narrow-band receiver designed to detect the electromagnetic wave produced by lightning or the electric field change which results. The counter detects the flash, computes its range, and displays the number of discharges occuring in preselected ranges. The most popular ranges used are 100, 50, 25, and 10 miles. By observing the number of discharges per range, one can determine the distance of the storm from the site.

Counters that detect the radiated wave follow the relationship that the amplitude decreases linearly with distance. These counters have a greater range than those that sense electric field changes. However, the electrostatic field change decreases with the cube of the distance, resulting in greater accuracy in the decreased range.

The flash counter also has limitations. The range information is based on the theory that each discharge is of average intensity, although Berger (1975) and others indicate these values can vary greatly (7 to 10 dB standard deviation). In addition, nearby intra-cloud lightning may be detected as a distant earth flash. Although the counters do not indicate direction of storm movement, the device can be used effectively at facilities where storms do not generally build overhead and the mature storms moving into the area always come from the same direction.

AZIMUTH/RANGE LOCATOR

The location of distant lightning by using two crossed loops arranged at right angles is an old, well established technique. The system responds to a narrow band in the VLF frequency range. The range of lightning location is determined the same way as does the spherics flash counter. To determine bearing, the ratio of signal amplitudes are compared. A monopole electric field antenna furnishes polarity information to eliminate the 180° ambiguity in bearing. The resulting location is generally displayed as a point on a CRT. The technique is relatively simple and has been used in land-based

systems and in aircraft. Some variations of this technique use a wide-band amplifier tuned to somewhat higher frequencies to eliminate some problems caused by the reradiation of the magnetic field.

Although the conventional crossed-loop locator has an effective range of up to 200 kilometers (km), it is inaccurate at close ranges. Bearing errors have been known to exceed 20° at ranges of less than 150 km due primarily to the horizontal components of the electromagnetic wave and reradiation of the wave by metallic bodies, buried conductors, or the ionosphere. Krider, et. al. (1976) devised a wideband system that samples the magnetic field at its peak, where the lightning channel is most vertical. However, this system is still subject to bearing errors due to the reradiation of the wave which can be a problem at military facilities where security fences are used extensively.

CROSSED-LOOP TRIANGULATION

The accuracy of a crossed-loop location system can be enhanced greatly by using three or more antennas to locate the same flash. Figure (3) is a block diagram of a typical triangulation network. The range and bearing information from each of the antennas is fed to a central computer where the data is analyzed statistically and the ground strike location is determined and plotted on a CRT.

Lightning Location and Protection Inc., the manufacturer of the crossed-loop triangulation system, has developed software to try to reduce the effect of the reradiated waves. The system is used operationally by the Bureau of Land Management and several utility companies, and is also used as a research tool by many studying key lightning parameters.

The major disadvantages to this type of system is the cost and the criticality of antenna site selection. The optimum site for an antenna would be in a large field with no buried conductors or metallic objects nearby. Sites such as this are not common at most military facilities. However, triangulation networks now cover a large portion of the United States and in these areas use of the system could be economical.

TIME-OF-ARRIVAL TRIANGULATION

The time-of-arrival (TOA) triangulation network is identical to the crossed-loop network with the exception of the detection method used. In a TOA network, each antenna detects the spherics wave and labels the time the wave was received. The information from each antenna is transferred to the central computer where it is analyzed and plotted. The system operates in the VHF frequency band and is not affected by reradiated waves. Pierce (1977) states that this is a very powerful technique, but it has not been practical to implement in the past. Today's technology in electronics now allows the precise timing of the received signal and therefore very accurate lightning location over a large area. The major limitation of this system to date is that it is not a proven system as is the crossed-loop system, but preliminary evaluations show it to be promising. In addition, antennas for the TOA network are not site sensitive, which may be important at military facilities.

BLOCK DIAGRAM OF TRIANGULATION LIGHTNING DETECTION NETWORK

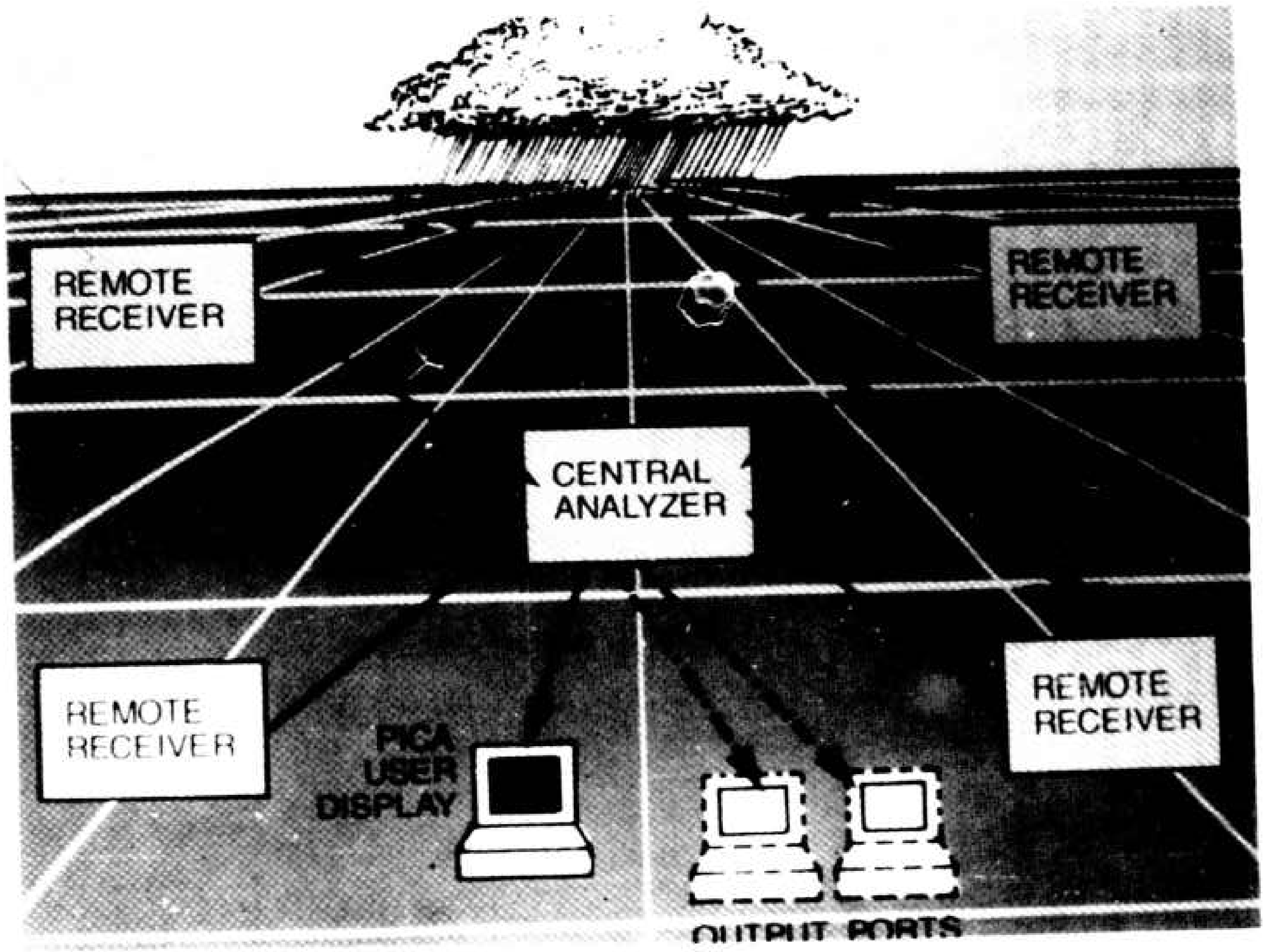

Figure 3 (Courtesy of Atlantic Scientific Corporation)

III. EVALUATION OF TECHNIQUES

The Bureau of Mines sponsored an evaluation of six lightning warning devices during the summer of 1979 because of their concern in using detonators in blasting operations. The results of the study were reported by Johnson, et. al., in the May 1982 Journal of Applied Meteorology. These results are summarized in tables 1 and 2.

Data were gathered from three locations which have different types of characteristic storms. As shown in these tables, the triangulation locator exhibited the best overall performance, although it is the most expensive to operate. In addition, the radioactive probe and field mill consistently gave 20 minutes or greater warnings, but both had high failure-to-alarm rates. In summary, no system was found to be ideal in all categories. A decision on the type of system required by a facility should be based on a tradeoff of the characteristics which are most important to the operations being conducted at the facility and the systems ability to meet these criteria.

TABLE 1

FRONTAL TYPE STORM SUMMARY

DEVICE	AVERAGE WARNING (min)	FALSE ALARM RATE (%)	FAILURE TO ALARM RATE (%)	ALARM RELIABILITY (%)	TIME TO CLEAR (min)
RADIOACTIVE	33	9	9	91	15
FIELD MILL	40	18	9	82	22
CORONA POINT	-20	27	55	73	-19
FLASH COUNTER	35	0	9	100	44
TRIANGULATION LOCATOR	21	0	9	100	5
AZIMUTH/RANGE LOCATOR	121	73	0	27	109

(FROM BUREAU OF MINES EVALUATION)

TABLE 2

CONVECTION TYPE STORM SUMMARY

DEVICE	AVERAGE WARNING (min)	FALSE ALARM RATE (%)	FAILURE TO ALARM RATE (%)	ALARM RELIABILITY (%)	TIME TO CLEAR (min)
RADIOACTIVE	28	0	10	100	-8
FIELD MILL	27	0	15	100	9
CORONA POINT	-15	0	80	100	22
FLASH COUNTER	32	0	55	100	-18
TRIANGULATION LOCATOR	21	0	6	100	-4
AZIMUTH/RANGE LOCATOR	30	0	5	100	17

(FROM BUREAU OF MINES EVALUATION, 1979)

MOUNTAINOUS TYPE STORM SUMMARY

DEVICE	AVERAGE WARNING (min)	FALSE ALARM RATE (%)	FAILURE TO ALARM RATE (%)	ALARM RELIABILITY (%)	TIME TO CLEAR (min)
RADIOACTIVE	21	0	27	100	33
FIELD MILL	50	0	20	100	67
CORONA POINT	-20	0	80	100	40
FLASH COUNTER	-4	0	64	100	23
TRIANGULATION LOCATOR	20	0	9	100	0
AZIMUTH/RANGE LOCATOR	101	82	0	18	117

(FROM BUREAU OF MINES EVALUATION, 1979)

IV. SUMMARY/CONCLUSIONS

In summary, the major lightning detection techniques have been reviewed and their respective limitations discussed. No single system or single technique has been found that can reliably detect a mature storm moving into the area and a storm that may be building directly overhead. The field mill and radioactive probe were found to have promise, but were not 100% reliable. Although expensive to purchase and operate, the traingulation locator is the most sophisticated technique available, but cannot detect storms building directly overhead.

The optimum solution to the advance warning of potential lightning hazards seems to be a combination of techniques based on spherics detection and the electric field measurement. The selection of equipment should be based on actual detection requirements, frequency of lightning activity, scheduling criticality, and cost. At this time, it appears that the most reliable combination available would be a triangulation network for long range detection and tracking of mature storms, with a field mill array to detect the development of dangerous fields building directly overhead.

BIBLIOGRAPHY

Anderson, R. B., "Measuring Techniques," Lightning, Volume 1-Physics of Lightning (edited by R. H. Golde), Academic Press, London, 1977.

Barlow, J. S., Frey, Jr, G. W., and Newman, J. B., "Very Low Frequency Noise Power From the Lightning Discharge," Office of Naval Research, Contract No. N6-ONR-24311, September 1954, pg. 187-203.

Berger, K., "The Earth Flash," Lightning, Volume 1-Physics of Lightning, (edited by R. H. Golde), Academic Press, London, 1977.

Boggs, S. A., and Stone, G. C., "Fundamental Limitations in the Measurement of Corona and Partial Discharge," IEEE Transactions on Electrical Insulation, Volume EI-17, No. 2, April 1982, pg. 143-150.

Brooks, M., and Ogawa, T., "The Cloud Discharge," Lightning, Volume 1-Physics of Lightning (edited by R. H. Golde), Academic Press, London, 1977.

Burger, J. P., and Rost, D. L., "Preliminary Report of the Initiation of Various Types of Electroexplosive Devices by Induced Lightning," NTIS Report AD 827746, 1967.

Chalmers, J. A., Atmospheric Electricity, Pergamon Press LTD, Oxford, 1967.

Chauzy, S., and Raizonville, P., "Space Charge Layers Created by Coronae at Ground Level Below Thunderclouds: Measurements and Modeling," Journal of Geophysical Research, Volume 87, No. C4, April 20, 1982, pg. 3143-3148.

Cianos, N., and Pierce, E. T., "Methods for Lightning Warning and Avoidance," SRI Technical Report, May 1974.

Cianos, N., and Pierce, E. T., "A Ground-Lightning Environment for Engineering Usage," Stanford Research Institute, Technical Report TR-No.1.

Dennis, A. S., and Pierce, E. T., "The Return Stroke of the Lightning Flash to Earth As a Source of VLF Atmospherics," Journal of Research NBS/USNC-URSI, Volume 68D, No. 7, July 1964, pg. 777-794.

Deparment of The AirForce, AFR 127-100, "Safety Manual,".

Department of Defense, MIL-HNDK-419, "Grounding, Bonding, and Shielding for Electronic Equipments and Facilities," Volume 1, 21 January 1982.

Department of Defense, MIL-HNDK-419, "Grounding, Bonding, and Shielding for Electronic Equipments and Facilities," Volume 2, 21 January 1982.

Durfee, G. H., "Effects of Lightning on Electrostatic Fuzing Systems," General Electric Technical Report TR-R59SD390, July 1959.

Gething, P. J. D., Radio Direction-Finding, Peter Peregrinus LTD, London, 1978.

Golde, R. H., Lightning Protection, Edward Arnold LTD, London, 1973.

Greene, D. R., and Clark, R. A., "An Indicator of Explosive Development in Severe Storms," 1971.

Gumley, J. R., "Lightning Prediction Techniques," Electrical Engineering Transactions, Institute of Engineers, Australia, 1973, pg. 13-18.

Horner, F., and Bradley, P. A., "The Spectra of Atmospherics From Near Lightning Discharges," Journal of Atmospheric and Terrestrial Physics, Volume 26, 1964, pg. 1155-1166.

Johnson, R. L., Janota, D. E., and Hay, J. E., "An Operational Comparison of Lightning Warning Systems," Journal of Applied Meteorology, May 1982, pg. 703-707.

Kasemir, H. W., "Final Report to KSC Contract Number CC-59753," NOAA-APCL Technical Report June 1976.

Krider, E. P., Noggle, R. C., and Uman, M. A., "A Gated Wideband Magnetic Direction-Finder for Lightning Return Strokes," Journal of Applied Meteorology, Volume 15, 1976, pg. 302-306.

Latham, J., and Stromberg, I. M., "Point-Discharge," Lightning, Volume 1-Physics of Lightning (edited by R. H. Golde), Academic Press, London, 1977.

Lee, W. R., "Lightning Injuries and Death," Lightning, Volume 2-Lightning Protection (edited by R. H. Golde), Academic Press, London, 1977.

Malan, D. J., Physics of Lightning, English Universities Press LTD, London, 1963.

Moore, C. B., Brook, M., and Krider, E. P., "A Study of Lightning Protection Systems," The Office of Naval Research Contract No. N00014-78M-0090 Final Report, October 1982.

Naval Sea Systems Command, NAVSEA OP-5, "Ammunition and Explosives Ashore," Volume 1, Fourth Revision, 15 October 1974.

Naval Surface Weapons Center, "Ammunition Evolution Curtailment at Sea Due to Thunderstorms; Criteria for," NSWC ltr DT-52:RAV:ac 8000, SAFEORD, DU 1L - 2C, 17 September 1975.

Naval Surface Weapons Center, "Thunderstorm Hazards to Ordnance," NSWC ltr N42:MAG:rsm 8020 of 28 August 1980.

Nordgard, J. D., and Chen, C. L., "Lightning-Induced Transients on Buried Shielded Transmission Lines," 1975 IEEE Symposium on EMC, September 1975, pg. 3AIC1-3AIC3.

Orville, R. E., and Salanave, L. E., "Lightning Spectroscopy - Photographic Techniques," Applied Optics, Volume 9, August 1970, pg. 1775-1781.

Parekh, H., and Srivastava, K. D., "Effect of Avalanche Space Charge Field on the Calculation of Corona Onset Voltage," IEEE Transactions on Electrical Insulation, EI-14 No. 4, August 1979, pg. 181-192.

Parker, L. W., and Kasemir, H. W., "Airborne Lightning Warning Systems: A Survey," AFGL-TR-80-0226, July 1980.

Pierce, E. T., "Atmospherics and Radio Noise," Lightning, Volume 1-Physics of Lightning (edited by R. H. Golde), Academic Press, London, 1977.

Pierce, E. T., "Latitudinal Variation of Lightning Parameters," Journal of Applied Meteorology, Volume 9, February 1970, pg. 194-195.

Pierce, E. T., "Lightning Location and Warning Systems," Lightning, Volume 2-Lightning Protection (edited by R. H. Golde), Academic Press, London, 1977.

Prentice, S. A., "Frequency of Lightning Discharges," Lightning, Volume 1-Physics of Lightning (edited by R. H. Golde), Academic Press, London, 1977.

Salanave, L. E., "The Infrared Spectrum of Lightning," IEEE Region Six Conference Record, 1966.

Salanave, L. E., "The Optical Spectrum of Lightning," Science, Volume 134, No. 3488, 3 November 1961, pg. 1395-1399.

Schonland, Sir Basil, The Flight of Thunderbolts, 2nd edition, Claredon Press, Oxford, 1964.

Standler, R. B., and Winn, W. P., "Effects of Coronae on Electric Fields Beneath Thunderstorms," Quarterly Journal of the Royal Meteorological Society, Volume 105, No. 443, January 1979, pg. 285-302.

Stansfield, R. G., "Statistical Theory of D. F. Fixing," Ministry of Works Technical Report, 1947.

Uman, M. A., Lightning, McGraw-Hill, New York, 1969.

Uman, M. A., Lin, Y. T., and Krider, E. P., "Errors in Magnetic Direction Finding Due to Nonvertical Lightning Channels," Radio Science, Volume 15, No. 1, January - February 1980, pg. 35-39.

U. S. Army Materiel Development and Readiness Command, DARCOM-R 385-100, "Safety Manual", 17 August 1981.

Weidman, C. D., and Krider, E. P., "The Fine Structure of Lightning Return Stroke Waveforms," Journal of Geophysical Research, Volume 83, No. C12, December 20, 1978, pg. 6239-6247.

Winn, W. P., and Byerley, III, L. G., "Electric Field Growth in Thunderclouds," Quarterly Journal of the Royal Meteorological Society, Volume 101, 1975, pg. 979-994.